Geomechanical Understanding of Fault Zone Mixing and Implications for Fluid Flow Along Faults in Sedimentary Rocks

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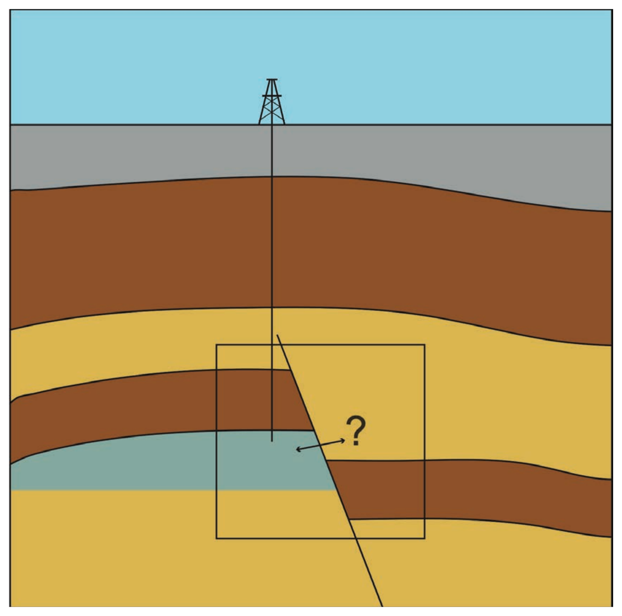
Abstract

Faults can serve as barriers or conduits to fluid flow, significantly impacting fault strength and influencing the nucleation and rupture of both natural and induced earthquakes. Traditional methods for assessing fault fluid flow behavior focus on measuring the clay or shale content entrained along fault planes. While these methods have some empirical basis, they have limited predictive capability due to their inability to accurately model the deformation processes that govern the composition, textures, and other properties of fault zones that affect fluid flow. To address these challenges, we use a physics-based Distinct Element Method (DEM) model, which enhances our understanding of these phenomena. By calibrating the DEM model with laboratory-based sand and clay box models, we examine the effects of grain size contrast and mechanical strength differences between sand and shale horizons on fault zone properties. Our findings indicate that variations in grain size and mechanical strength significantly affect fault zone width and the localization of secondary fracturing. These variations, in turn, have profound implications for shale and clay entrainment, which are considered to control fluid flow behavior within fault zones. Ultimately, we expect that the DEM models will support the development of a more robust approach to understanding and predicting fluid-related fault zone properties that may influence rupture dynamics. This, in turn, can provide valuable insights to help avoid or limit risks associated with fluid leakage and induced seismicity in various energy and environmental applications, such as subsurface energy and carbon storage.

Introduction



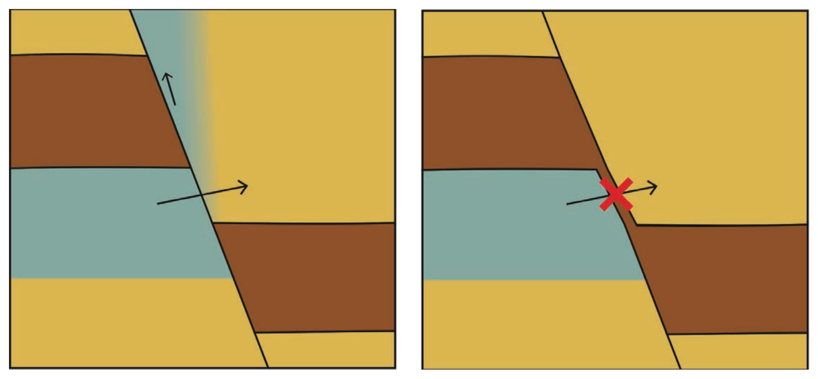


Figure 1. Schematic examples illustrating significant fault scenarios: an unknown fault on the left, if the fault were to leak fault on the top right, and if the fault were to seal on the top right.

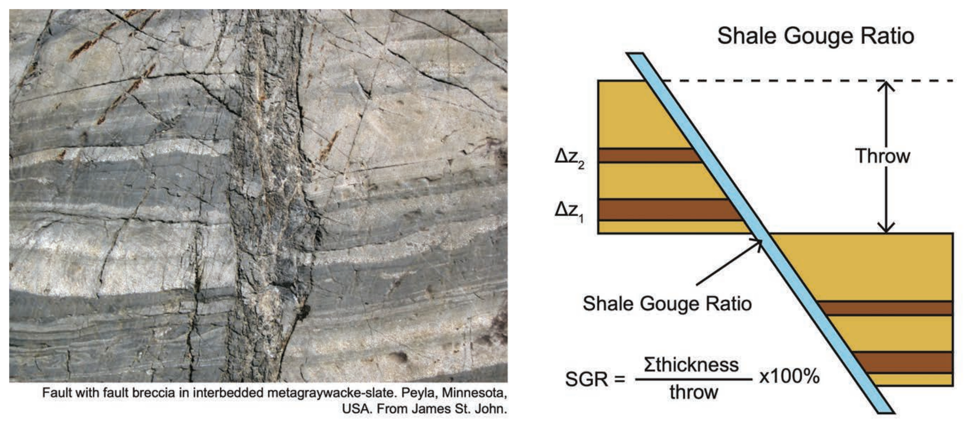


Figure 2. Example of a natural fault mixing zone on the left, with the method for calculating the Shale Gouge Ratio on the right. Note the complexity of the natural case, which is not captured in the modeled approach.

Methodology

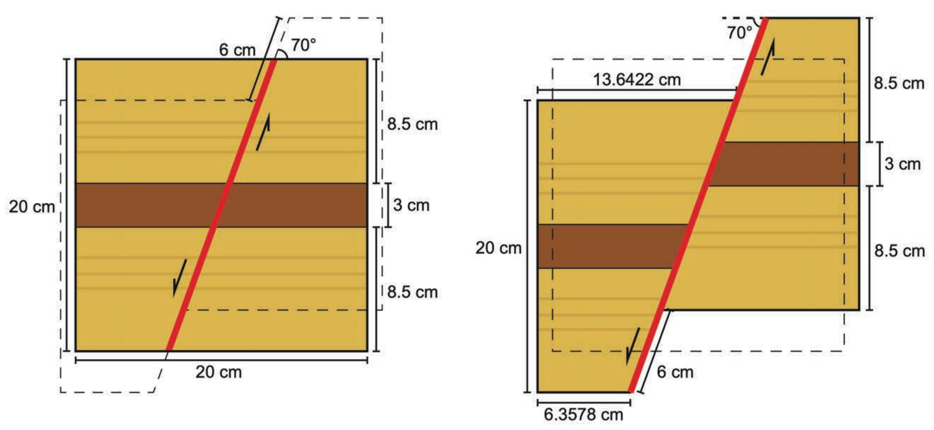


Figure 3. Model geometry setup for the main mixing analysis, based on previous work by Schmatz et al., 2010 to evaluate three styles of fault zone mixing behavior.

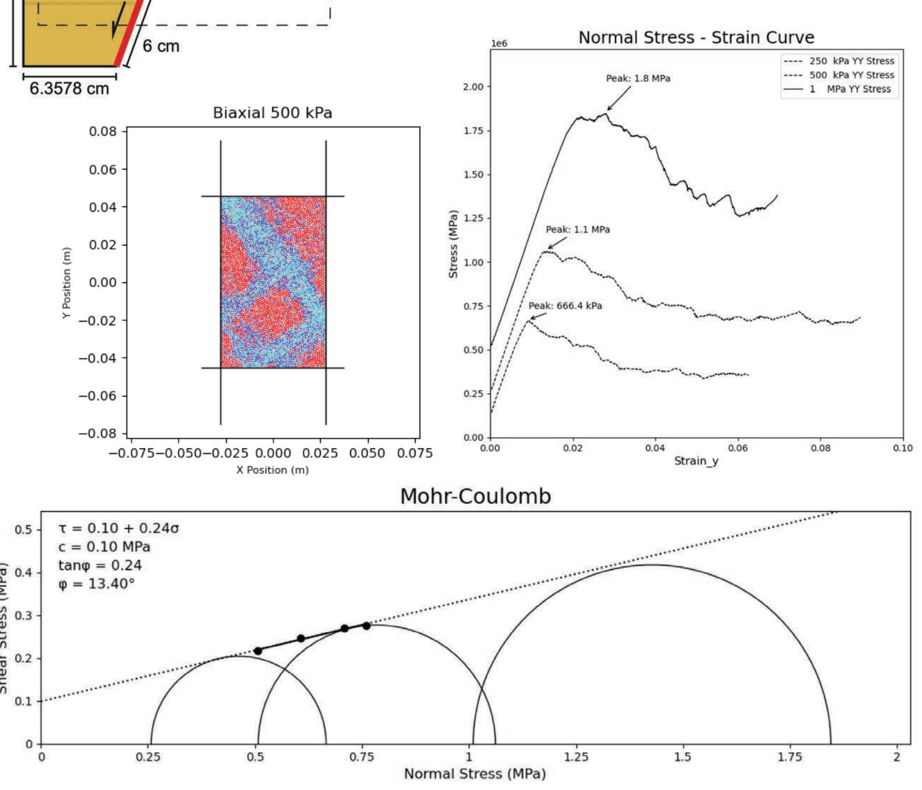


Figure 4. Mechanical summary results from biaxial and direct shear tests on the modeled materials. Stress-strain plots are shown for a range of confining pressures. The Mohr-Coulomb failure criterion is derived and plotted based on the parameters obtained from the laboratory-calibrated tests that passed validation criteria.

Results

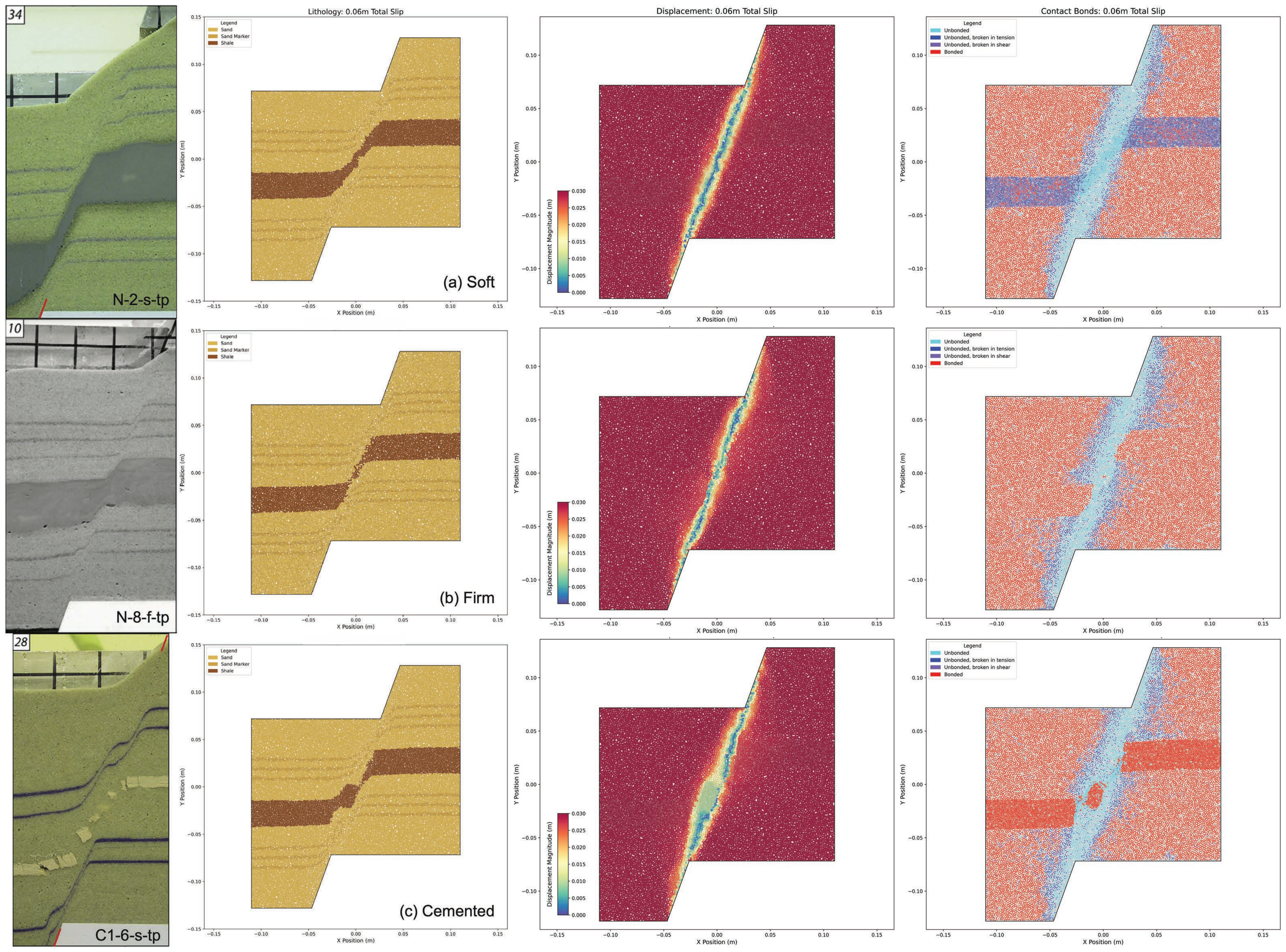


Figure 5. Fault zone clay mixing models reproduced from the laboratory case study by Schmatz et al. (2010). The top row shows mixing from (a) soft clay, the middle from (b) firm clay, and bottom from (c) cemented clay. For each scenario, the original case study is presented on the far left, the lithology of the DEM models in the center left, particle displacement in the center right, and the state of contact bonds on the far right.

Key takeaways:

- Mixing within the fault zone varies with the contrasting strength properties of the modeled horizons.
- Fault zone shape is strongly influenced by the ability to localize strain and can demonstrate pronounced asymmetry and nonlinearity early in fault zone evolution.
- The fault damage zone inferred by bond assemblages is wider than the primary slip surface in all cases and can also exhibits nonlinear behavior.

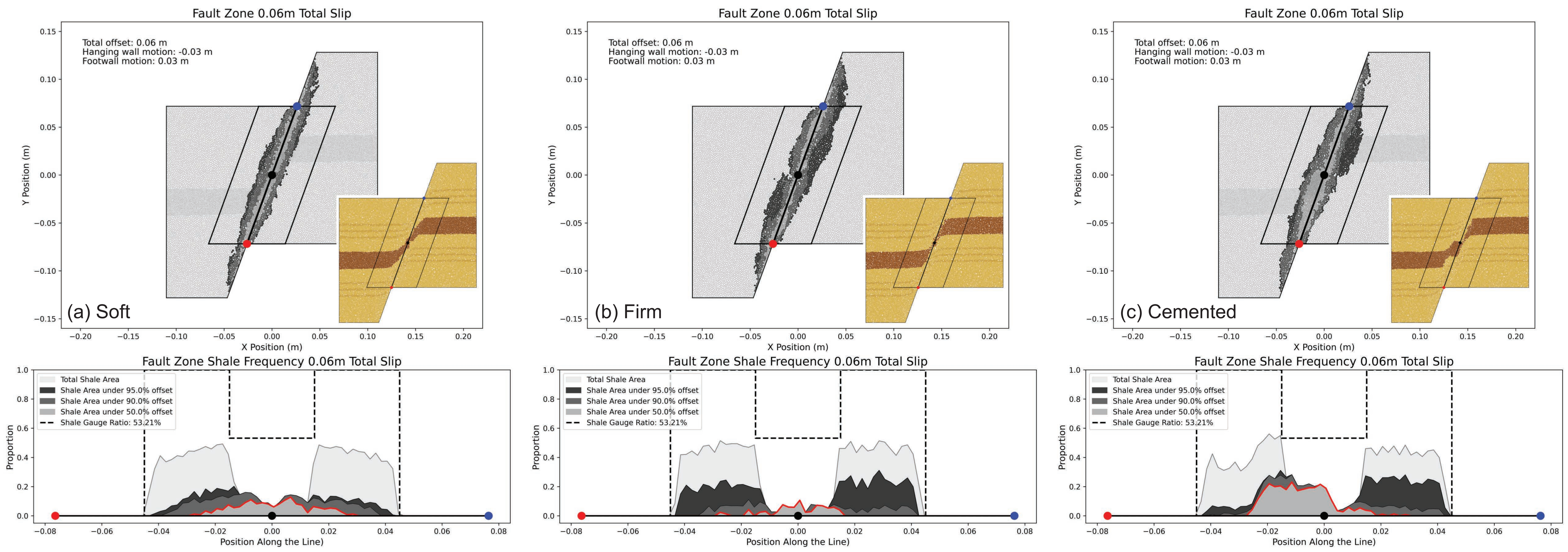


Figure 6. Fault zone mixing as a function of displacement. Particles experiencing less displacement than the total model offset are considered entrained within the fault zone and are used to quantify mixing. The panels show, from left to right: (a) soft clay, (b) firm clay, and (c) cemented clay scenarios. The top plot shows the entrained particles as a percent of fault displacement for 95%, 90%, and 50% cases. Clay content of the fault calculated by the projecting the volume of clay binned by the corresponding fault zone. Shale Gouge Ratio (SGR), plotted as a dashed line.

Conclusions

Our study demonstrates the capability of mechanical models to replicate fault zone development and shale entrainment consistent with analog experiments, providing insight into three distinct styles of sand and shale deformation. By varying grain size and strength parameters, we captured a spectrum of fault behaviors—from the highly deformable, clay-enriched cores in soft clay, to structurally robust, multi-slip zones in cemented shales. Through rigorous Mohr-Coulomb calibration, our Discrete Element Method (DEM) models accurately reproduce the mechanical response of natural rocks, underscoring the importance of careful calibration for real-world prediction. Unlike simplified approaches like the Shale Gouge Ratio, our models reveal that different deformation styles lead to complex and variable clay distributions within the fault zone, directly informing our understanding of fluid migration and sealing potential. This nuanced, process-based modeling advances our ability to assess fault zone stability and provides a foundation for more reliable hazard forecasting and resource management in both energy and environmental applications.

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